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Numerical Study of Heat Transfer for Gravity-Driven Particle Flow along a Vertical Oscillating Pin-Fin Plate

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Nowadays, moving bed heat exchanger (MBHE) is being gradually applied in the fields of industrial waste heat recovery and solar energy utilization, due to its easy production of clean energy and low cost. However, the heat transfer performance of the MBHE is relatively poor. In the present paper, the heat transfer performance of gravity-driven particle flow in a pin-fin plate heat exchanger unit (PFPHEU) is numerically studied using discrete element method. The effects of pin-fin and plate oscillation on the heat transfer of gravity-driven particle flow along a vertical plate are carefully analyzed. The results show that, the heat transfer coefficient of the static PFPHEU is about 12.5 % less than that of the PWPF due to the higher porosity around the pin-fin compared to the plate without pin-fin (PWPF). The plate oscillation can significantly improve the particle filling rate around pin-fins and enhance the thermal dispersion of particle flow. The heat transfer in a PFPHEU is enhanced, and the heat transfer coefficient of PFPHEU increased by 87.6 % and 113.5 % compared with that of PWPF as the amplitude was 1 mm and 2 mm.

1. Introduction

In recent years, the world's energy and environmental problems have become increasingly prominent, which makes it very urgent to improve energy efficiency and sustainable energy development. Moving Bed Heat Exchanger (MBHE), with the advantages of low cost and clean energy, is gradually applied to industrial high temperature waste heat recovery (Liu et al., 2015) and Concentrated Solar Power (CSP) (Baumann and Zunft, 2015). Moving Bed Heat Exchanger (MBHE) is generally used for energy recovery of particle flow driven by gravity. Improving the heat transfer performance and particle flow are the key issues in MBHE research.

The arrangement of heat exchangers in MBHE can be roughly divided into horizontal or vertical tubes and vertical parallel plates. For horizontal tubes, Liu et al. (2015) found that the heat transfer performance of staggered heat exchanger was better and the heat transfer coefficient increased with the decrease of particle size or the increase of particle velocity by experiments. Nguyen et al. (2014) verified that finned tube is more conducive to improving heat transfer performance than non-fin tube by experiments. Morris et al. (2016) studied the flow and heat transfer performance of hexagonal tube by numerical simulation and the results showed that heat transfer is related to the solid concentration and particle size near the heat transfer surface. Bartsch et al. (2019) observed the stagnation zone and cavity zone at the top and bottom of the tube through experiments. Guo et al. (2019) found that vibration can enhance the renewal and contact between the particles and the tube wall and increase the heat transfer coefficient of particle flow around the tube. For vertical tubes and parallel plates, Hunt (1997) studied the effects of shear and particle mixing on the heat transfer coefficient of particle flow in vertical channels and found that the particle density near the wall is very important for heat transfer. Thomas et al. (1998) studied the heat transfer performance of horizontal and vertical tubes and flat surfaces and found that the flat surfaces afford higher heat transfer coefficients. Zheng et al. (2018) reported that the heat transfer process between the particles and the wall can be divided into high-speed phase, rapid phase and slow phase. Albrecht et al. (2019) studied the effects of particle size, operating temperature, and particle velocity on the shell-and-plate moving packed-bed heat exchanger.

Each arrangement of heat exchanger has its own advantages and disadvantages. When particles flow around a horizontal tube, the staggered tubes will disrupt the thermal boundary layer and strengthen the mixing of

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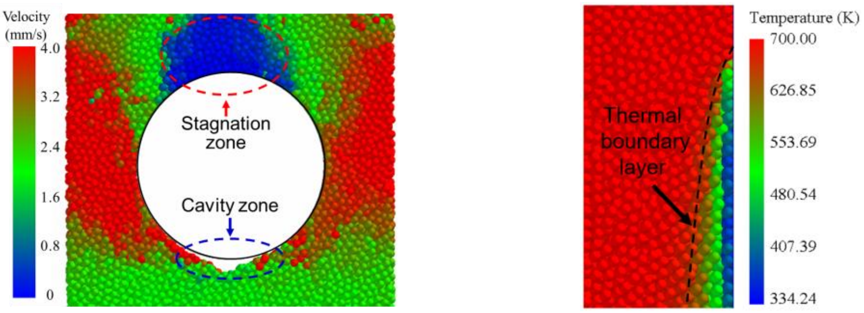
particles. However, the stagnation zone and cavity zone at the upstream and downstream of the tube will seriously affect the flow and heat transfer of particles, as shown in Figure 1a.



(a) (b)

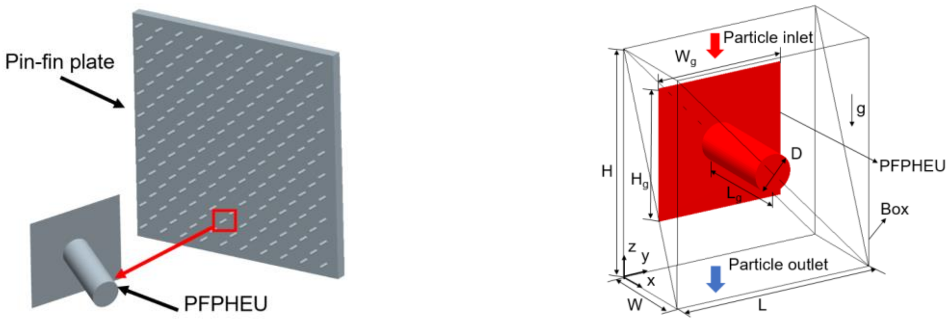
Figure 1: Flow characteristics of particles on different surfaces: (a) horizontal tube and (b) vertical tube or parallel plate

When particles flow along a vertical tube or plate, particles flow uniform but the thermal boundary layer develops continuously with the increase of the surface length (Albrecht et al., 2019), as shown in Figure 1b. At present, most studies focus on the influence of tube layout, tube shape, particle diameter and particle velocity on heat transfer in MBHE. The heat exchanger with the combination of tube and plate needs to be studied. Plate with cylindrical fins may have the advantage of both horizontal tube and vertical plate, which may enhance the heat transfer performance of MBHE. In this study, heat transfer performance of a pin-fin plate heat exchanger unit (PFPHEU) is carefully researched through discrete element method (DEM) by commercial software EDEM 2.6 (DEM Solutions, 2014), and the influence of oscillation is also considered. This work will contribute to the design and optimization of MBHE in the future.

2. Method and simulation

2.1 Methodology and simulation cases

Particle flow simulation methods can be divided into continuous method and discrete method. Compared with the continuous method, the discrete method can describe the particle flow in detail. It has become a better method to solve the problem of particle flow. However, due to the limitation of computational cost, DEM is usually used to simulate particulate flow locally. In this paper, the discrete element method (DEM) with heat transfer model is used to simulate the flow and heat transfer of particles flow around PFPHEU.



(a) (b)

Figure 2: (a)PFPHEU and (b) Geometry model

The heat transfer process between two particles and tube wall are including conduction, convection and radiation. The conduction includes conduction inside particle, contact conduction and conduction through gas film. Particles move slowly in MBHE and the velocity is only several millimeters per second (Zheng et al., 2018). Gas flow has little effect on particle flow (Srivastava and Sundaresan, 2003) and gas convection heat transfer accounts for a small proportion of heat transfer (Zhang et al., 2013). The flow and heat transfer of solid phase is the main concern in the current research. The heat transfer only considers conduction, ignoring convection and radiation.

The thermal resistance model adopted in this paper is based on the following assumptions: 1) the particle flow is composed of spherical particles with the same diameter; 2) the heat capacity of the gas can be neglected, and the temperature of a single particle is uniform; 3) the particles are wrapped by a gas film, and the film thickness is 0.1 d_p; 4) the heat transfer path between particles is along the radial direction of the particles; 5) the physical properties remain unchanged. A detailed description of the heat transfer model may refer to previous work by Tian et al. (2020).

The pin fin on the tube or plate are arrayed regularly. The PFPHEU and geometry model of PFPHEU used in the simulation are shown in the Figure 2. In order to simplify the model, the tube surface of the PFPHEU is regarded as a plane and the PFPHEU is in the middle of box. The physical model takes wall effect into account, and the particle size (d_p) is 0.8 mm. The geometric and physical parameters are shown in Table 1. In the simulation process, the temperature of the PFPHEU is constant and the wall of the box is adiabatic. The particle velocity is controlled at the outlet of the channel and remains constant in the vertical direction.

The random packing and high temperature particles are generated in the channel at initial. During the simulation process, particles flow by gravity with control in outlet and are cooled by the PFPHEU. Particle outlet velocity is 1 mm/s. The heat transfer is counted over time during simulation. The overall simulation lasts 30 s and the heat Q in finally 10 s is analysed. The heat transfer coefficient (h) of particle flow around PFPHEU is shown in Eq(1). Q is the heat transferred on tube wall; A_{PFPHEU} is the heat transfer area of tube wall; T_{in} is particle inlet temperature; T_{PFPHEU} is PFPHEU wall temperature; t is time.

$$h = \frac{Q}{A_{PFPHEU}\left(T_{in} - T_{PFPHEU}\right)\Delta t} \quad (1)$$

Table 1: Main parameters in simulation

name	parameter	value	parameter	value	name	parameter	value
	L (m)	0.02	L_g (m)	0.01		ρ/(kg/m^3)	2,848
	W (m)	0.01	W_g (m)	0.014		C_p/(J·kg^{-1}·K^{-1})	1,210
geometry	H (m)	0.02	H_g (m)	0.014	particle	k_p/(W·m^{-1}·K^{-1})	0.55
	D (m)	0.004	T_{PFPHEU}/(K)	300		E/(Pa)	5.5×10^8
						T_{in}/(K)	700
gas	k_f /(W·m^{-1}·K^{-1})	0.0257			time step	Δt/(s)	1.2×10^{-6}

(L, W and H is the particle flow channel length, width and height; H_g,W_g is the PFPHEU length and height; L_g is pin-fin length; D is pin-fin diameter; k_f is gas thermal conductivity; ρ is particle density; C_p is particle specific heat; k_p is particle thermal conductivity; E is Young modulus.)

2.2 Validation

In previous research, Tian et al. (2019) provided validation with the experimental data (Liu et al. 2015). In this paper, an additional cases for validating the DEM model was carried out. The heat transfer model adopted in

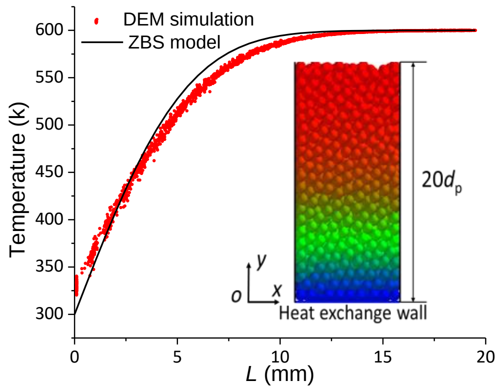


Figure 3: Comparison of temperature distribution with DEM simulation and ZBS model

this paper was compared with the ZBS model (Bauer and Schlünder, 1978), and the evolution of temperature distribution at t = 20 s in the vertical direction of the heat exchange wall are shown in Figure 3. The comparison shows that the temperature field calculated by DEM agrees well with the temperature field obtained by ZBS model, which shows that the heat transfer model used in DEM is reasonable.

3. Results and discussion

This study simulates the flow and heat transfer of PFPHEU under static and oscillation conditions. Continuous sinusoidal oscillations with different amplitudes in y direction are applied to PFPHEU at the beginning of particle flow of oscillation condition. To make more comparison, the static vertical non-fin plate heat transfer is simulated. Detailed simulation parameters for different cases are shown in Table 2. The heat transfer surface of case 1 is a plate without pin-fin (PWPF).

Table 2: Simulation parameters for different cases

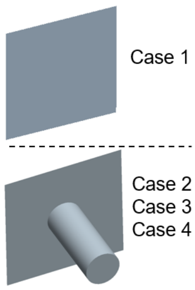
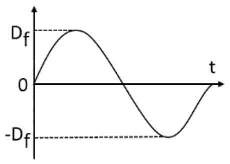
case	1	2	3	4	Heat exchange surface
Vibrating direction	static	static	y	y	
Frequency	0	0	3 Hz	3 Hz	
Amplitude	0	0	1 mm	2 mm	
Oscillation locus	none	none			

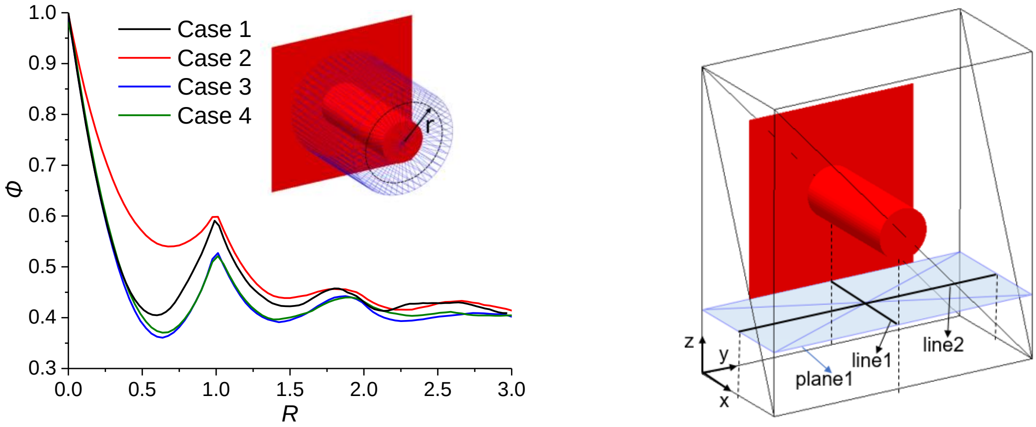
Table 3: Heat transfer characteristics for different cases

Simulation cases	1	2	3	4
Heat flux q (W)	17.0	24.5	31.9	36.3
Percentage increase of q (%)	0	44.1	87.6	113.5
Heat transfer coefficient h ($W\cdot m^{-2}\cdot K^{-1}$)	217	190	248	282
Percentage increase of h (%)	0	-12.5	14.6	30.0
Particle outlet temperature (K, plane1)	672	648	634	627

The heat transfer characteristics under different cases are shown in Table 3. The heat flux of PFPHEU is larger than that of PWPF because of the pin-fin increasing the heat transfer area. The oscillation can further increase the heat flow between the particles and PFPHEU. The static PFPHEU has the lowest heat transfer coefficient, which is about 12.5 % less than that of the PWPF. The heat transfer coefficient of PFPHEU with amplitude of 2 mm is the largest, which is 113.5 % higher than that of the PWPF. Oscillation can significantly enhance heat transfer, and the heat transfer coefficient increases with the amplitude increasing. The pin fin enlarges the contact area with particles, so the average temperature at the bottom of PFPHEU (plane1) is lower than that of the PWPF. The particle outlet temperature of PFPHEU is less than that of PWPF and the outlet temperature decreases further as the amplitude increases.

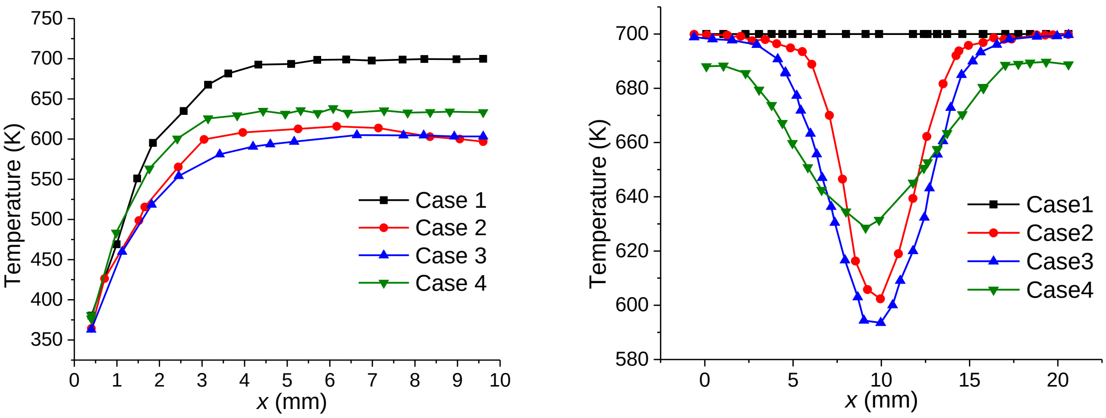
The time-averaged porosity perpendicular to the wall direction outside the pin-fin is shown in Figure 4a. R is equal to $(r\text{-}D/2)/d_p$ for case 2 - 4 and equal to r/d_p for case 1. r is the distance from a point outside the pin-fin to the pin-fin center or outside the plate wall. Due to the wall effect, the porosity fluctuates regularly near the pin-fin wall region (R < 2). Because PFPHEU in Case 2 is static, cavity zone is formed at the downstream of pin-fin, so its porosity is the highest, which is the reason for its lowest heat transfer coefficient, as shown in Table 3. When PFPHEU vibrates along the y direction, the movement of pin-fin makes the contact between particles and pin-fin closer, and the cavity zone at the downstream of pin-fin decreases or even disappears due to the movement of pin-fin. When the amplitude increased from 1 mm to 2 mm, the time-averaged porosity around the pin-fin did not change significantly.

Particle temperature distributions on lines 1 and 2 are shown in Figure 5a and Figure 5b. The position of line 1 is at y = 10 mm and z = 7 mm in the box as shown in Figure 4b. The position of line 2 is at x = 5 mm and z = 7 mm in the box. The temperature at line 1 of PFPHEU is obviously lower than that of PWPF because the pin-fin of PFPHEU can exchange heat with particles farther from the plate wall. When the amplitude increases, the residence time at line 1 decreases due to the increase of the movement range of the pin-fin, and the particle temperature at line 1 increases slightly compared with that of the static PFPHEU as shown in Figure 5a. The temperature distribution at line 2 is obviously different as shown in Figure 5b. The particle temperature of PWPF is kept constant at line 2. Compared with static PFPHEU at line 2, oscillation makes the temperature diffusion stronger.



(a) (b)

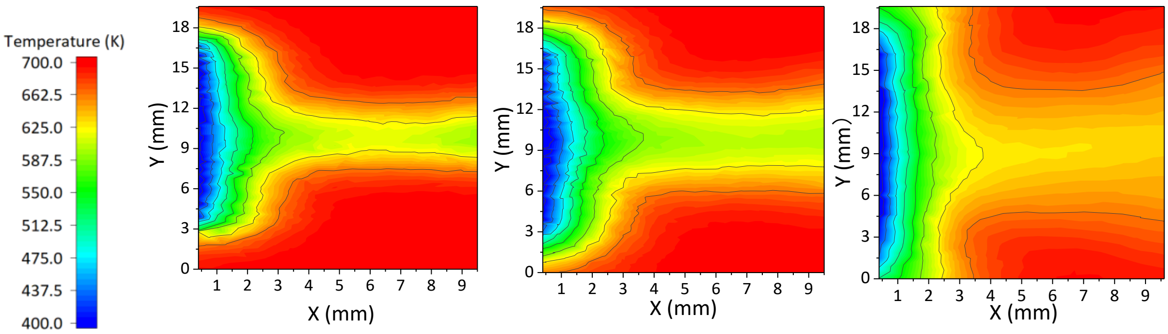
Figure 4: (a) Time-averaged porosity outside pin-fin and (b) Schematic diagram of plane1, line1 and line2.



(a) (b)

Figure 5: (a) Temperature distribution of line 1 and (b) Temperature distribution of line 2

Figure 6 is the temperature distribution at the bottom of PFPHEU (plane1) and the position of plane1 is at z = 7 mm in the box as shown in Figure 4b.



(a) (b) (c)

Figure 6: Temperature distribution at the bottom of PFPHEU (z = 7 mm):(a)case 2, (b) case 3 and (c) case 4

Compared with the static PFPHEU, the oscillation makes the pin-fin contact with more particles, and enhances the particle mixing. Compared with the case 3, the amplitude increasing makes the particle temperature under the pin-fin more uniform and the temperature gradient is smaller.

4. Conclusions

To enhance heat transfer in particle flow for MBHE, the heat transfer performance of PFPHEU is investigated in details by discrete element method. The major findings are summarized as below:

(i) The heat transfer coefficient of the static PFPHEU is about 12.5 % less than that of the PWPF due to the higher porosity around the pin-fin compared to the PWPF. But the PFPHEU with pin-fin increased the heat transfer area and significantly increased the heat flux between particles and PFPHEU.
(ii) Oscillation in *y* direction causes closer contact and reduce the porosity around pin-fin, which could enhance heat transfer and make the temperature diffusion stronger.
(iii) The oscillation can make the heat flux and heat transfer coefficient increase together under the condition of increasing the heat transfer area. The heat transfer enhancement is much remarkable as the amplitude increases in the *y* direction. When the amplitude was 1 mm and 2 mm, the heat transfer coefficient of PFPHEU increased by 87.6 % and 113.5 % compared with that of PWPF.

The present results show that oscillation and pin-fin can obviously improve the heat transfer performance of the plate which may indicate PFPHEU has a better application prospect in the MBHE. The effects of different oscillation directions, amplitudes and frequencies should be further studied in the future.

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